Improved Edge Performance in Magnetorheological Finishing (MRF)

presented to:

Technology Days in the Government
Mirror Development and Related Technologies
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John West, John Hraba

Dr. Philip Stahl

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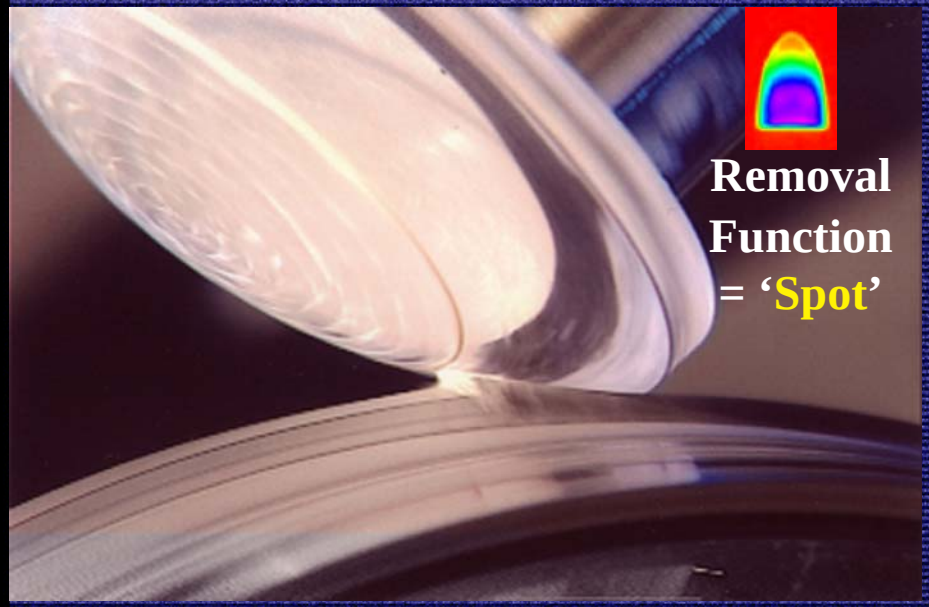
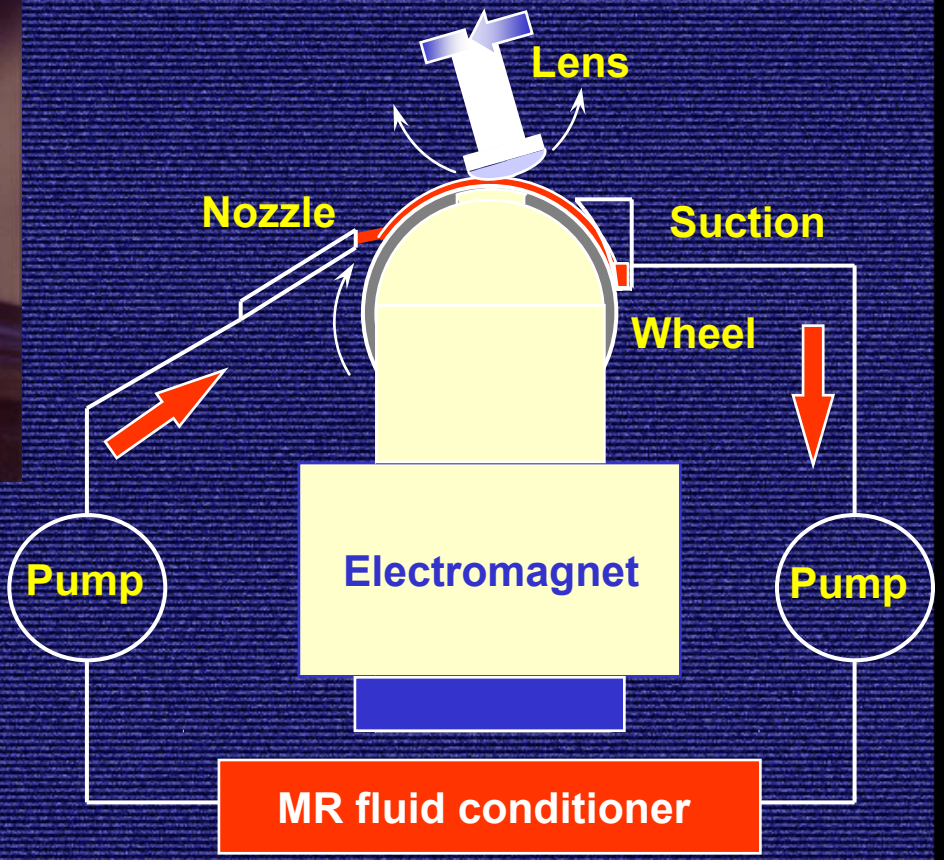
MRF – How it works





MRF – Breakthrough Technology

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The MRF polishing tool:

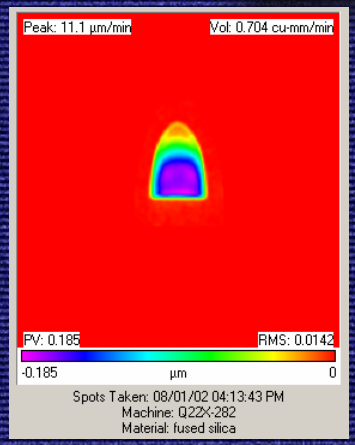
- never dulls or changes
- is interferometrically characterized
- is easily adjusted
- conforms to part shape - works on complex shapes (flat, sphere, asphere, cylinder…)
- has high removal rates
- removal based on shear stress so applies very low normal load on abrasive, improving surface integrity
- determinism leads to high convergence rate

- These attributes lead to a production oriented, deterministic, computer controlled polishing and figuring technique.

- Production proven: more than 90 machines worldwide

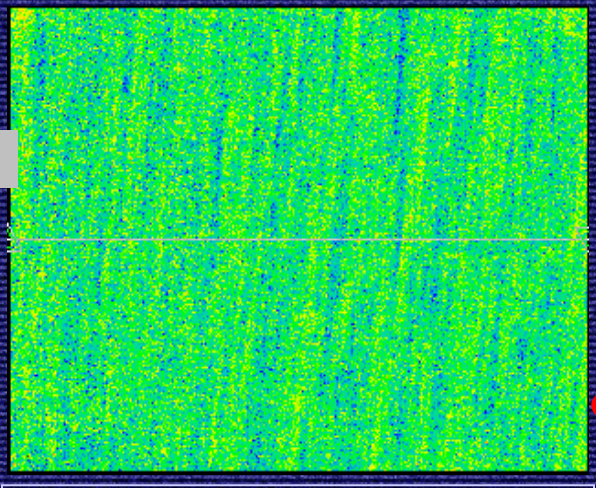
Removal rate and roughness

- **Removal rate dependent on:**
  - Material: FS, ULE, Zerodur, Si, SiC…
  - Process parameters
  - Machine/wheel size
- **Roughness**
  - MRF *smoothes* most materials
  - E.g. fused silica results:

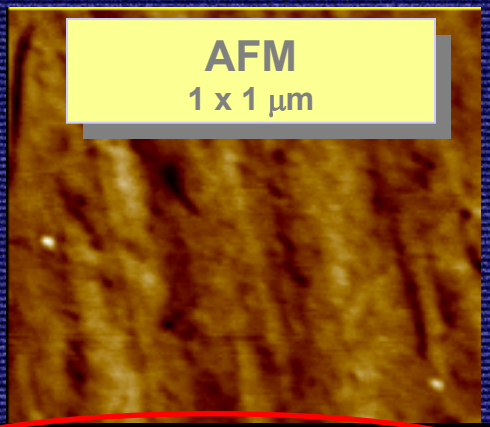


High Pass Filter (FTT Fixed – 12.5 1/mm)

Rmax	44.692	Å
Ra	2.829	Å
Rq	3.575	Å



New-View 5000
359 x 270 µm



AFM
1 x 1 µm

Img. Rms (Rq)	0.176 nm
Img. Ra	0.136 nm
Img. Rmax	1.884 nm

Example of MRF Capability: CaF2 Lenses for use in 157nm Lithography

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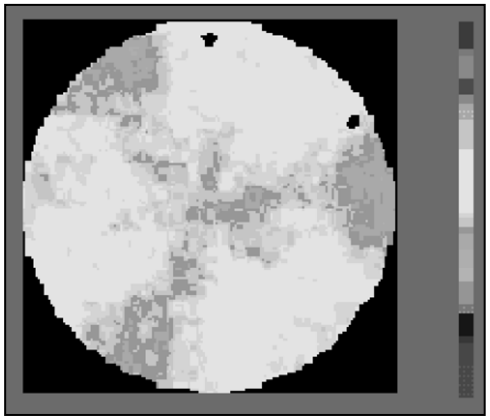
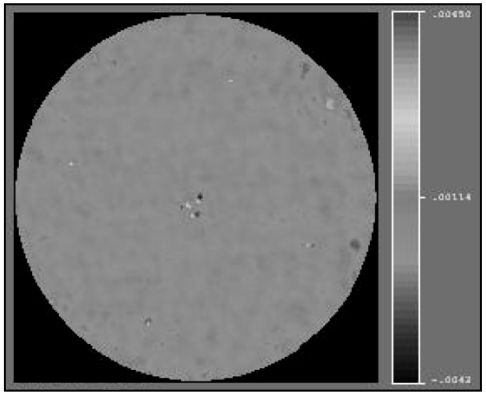


<111> Element
Surface figure: 0.57nm rms



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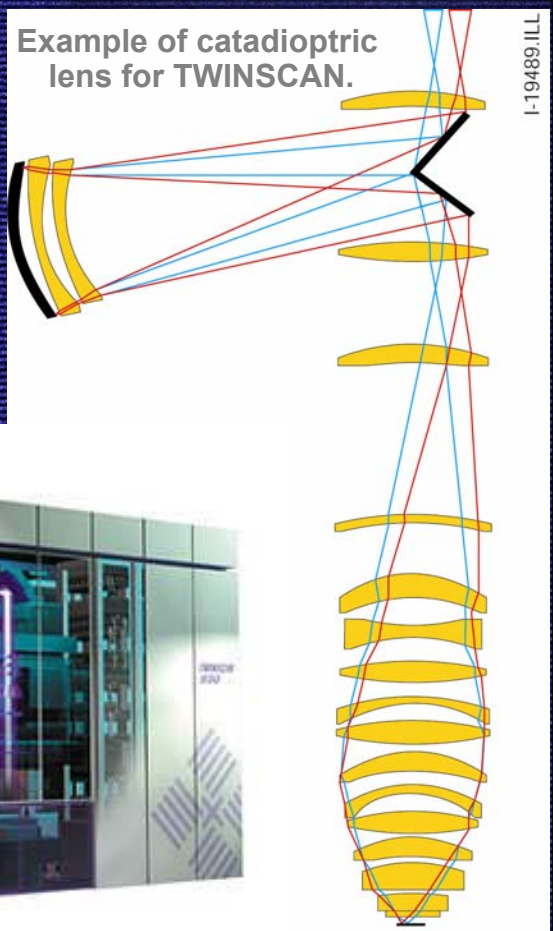
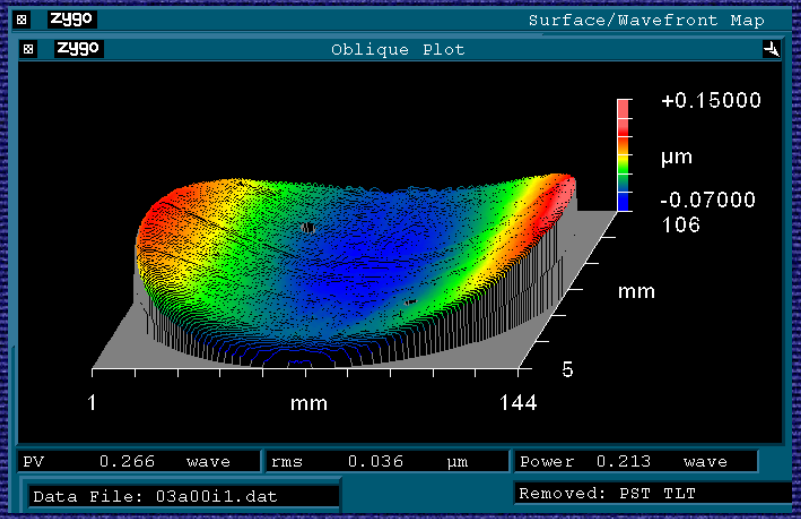
Surface figure: 0.63nm rms

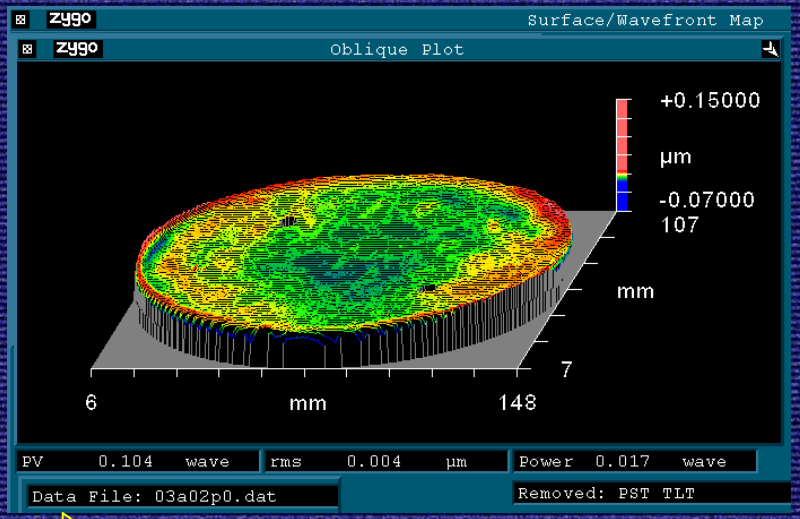


Jan Mulkens (ASML), et al., "Optical lithography solutions for sub-65 nm semiconductor devices", Proc. of SPIE, 5040; pp: 753-762, 2003.

Edge Effects - 6”x4” Elliptical Mirror Raster Polished

- MRF has demonstrated the ability to achieve very good results over part full aperture





PV = 0.27 λ

RMS = 36.4 nm

47.26 min

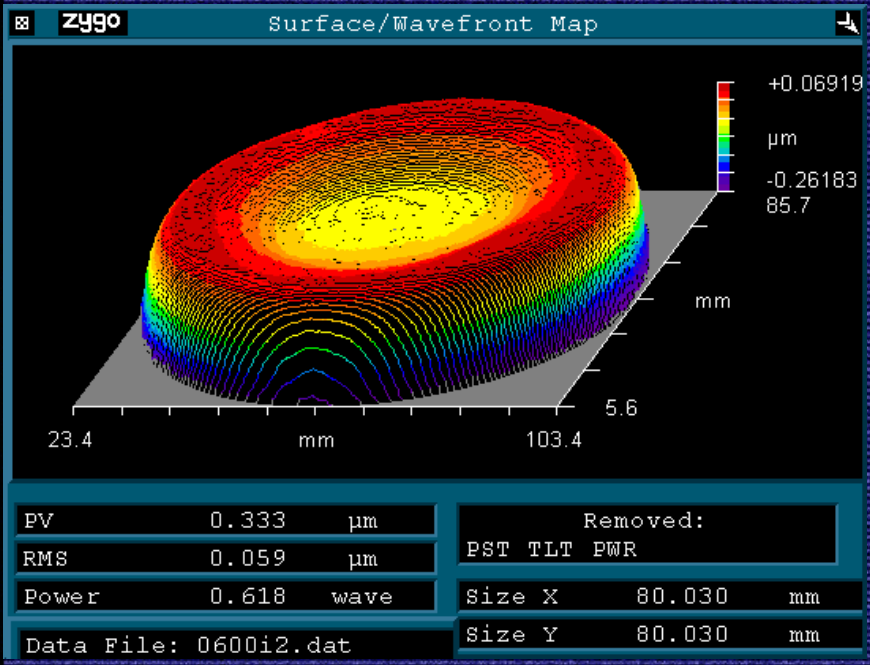
PV = 0.104 λ

RMS = 4.1 nm

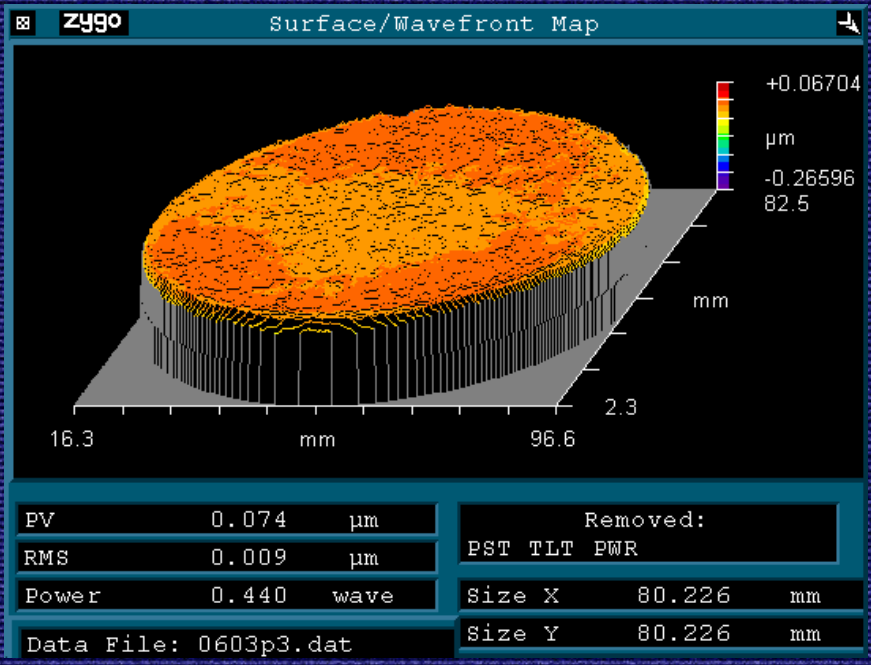
Full Visible Aperture (i.e. no edge exclusion)

80 mm Diameter 148.331mm radius concave sphere

Initial



Final



PV = 333 nm

RMS = 59 nm

185 min

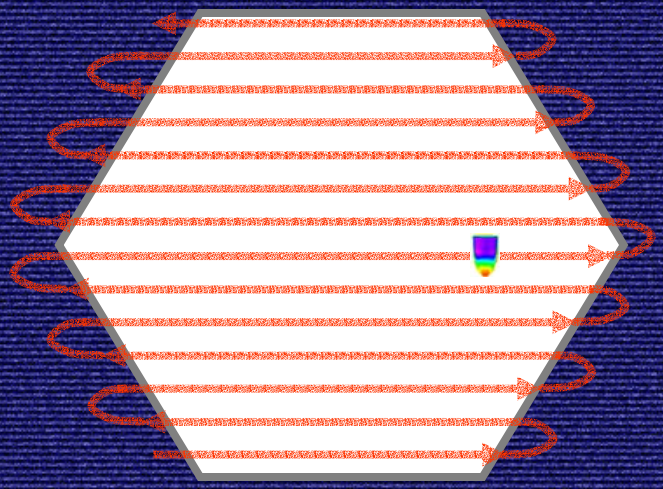
PV = 74 nm

RMS = 9 nm

Full Visible Aperture (i.e. no edge exclusion)

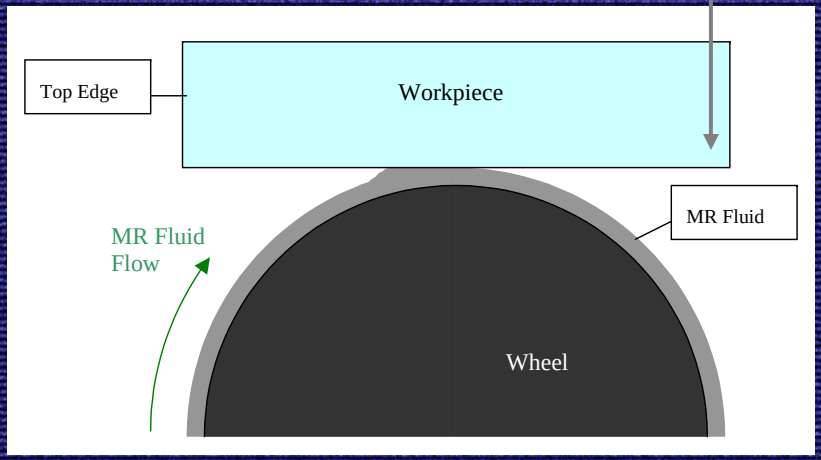
Fabricating Large Optics using MRF

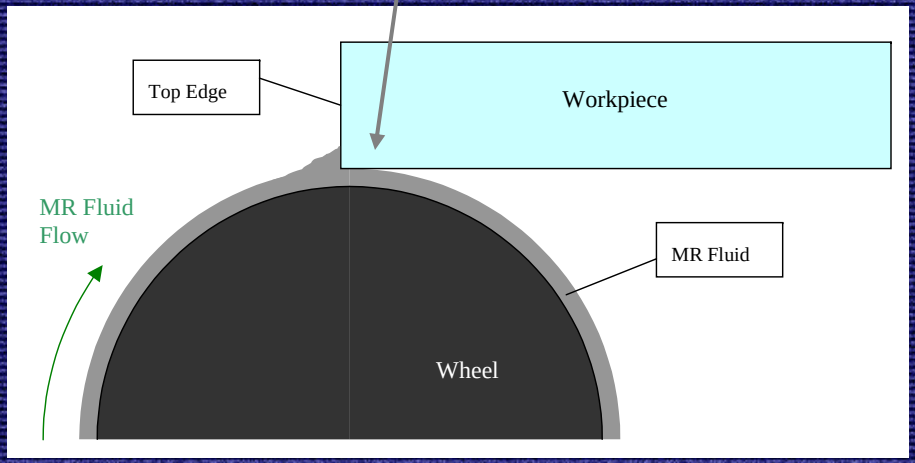
- Large *segmented* mirrors must have little or no edge exclusion
- Standard MRF has demonstrated good performance at edges for a variety of aperture sizes and shapes
- Work reported is to improve edges even further
- The primary goal is to understand process differences at the edge and develop an approach to account for them

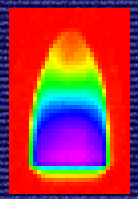


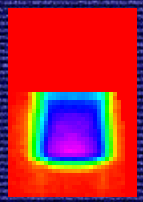
Causes of Edge Effects

- MR fluid flow over edges differs from flow over surface, leading to changes in the tool removal function ("spot")
- Edge performance at trailing edge, superior to leading edge due to flow characteristics









Polishing away from edges

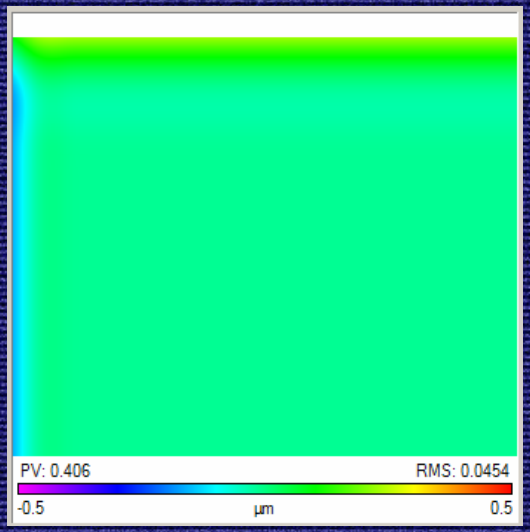
Polishing at edge

Methods of Eliminating Edge Effects

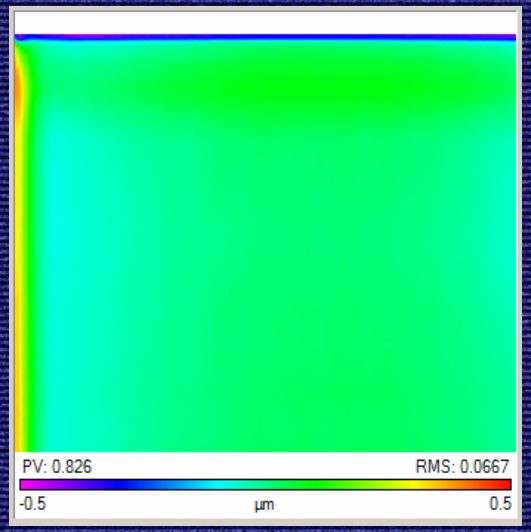
- **Edge extension: extend the workpiece surface with sacrificial hardware to eliminate the edges**
  - Usually impractical – extension height and slope must match workpiece exactly
  - Some benefit, but not pursued for above reasons
- **Variable plunge depth: use a smaller spot near edges**
  - Difficult to implement in software, but should provide best results
  - Planned Phase II activity
- **Edge spot characterization: model spot changes near edges and adjust dwell schedule**
  - More difficult to implement, results expected to be similar to variable plunge depth
- **Removal map modification: leave edge regions intentionally "high," and correct with smaller spot**
  - Simplest to implement, but requires additional iteration

Edge Spot Characterization

- Predict the variation of the spot at edges, and adjust the dwell schedule to compensate
- Spot variation at edges is complex and difficult to predict
- Prediction significantly different from actual, so method is not sufficient
- Work on this approach stopped for now



Predicted removal map



Actual removal map

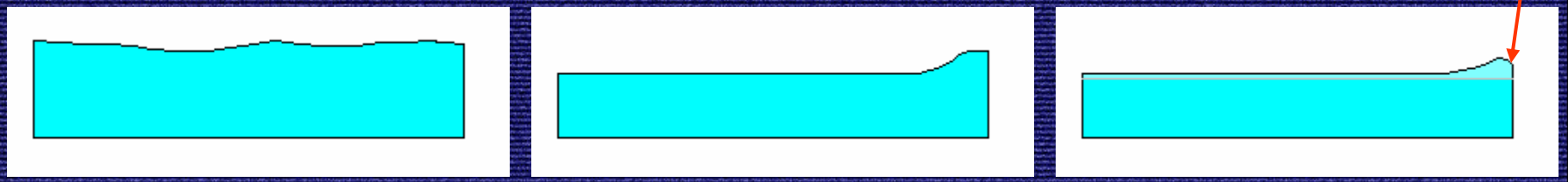
Removal Map Modification

- **Where rolled edges are anticipated, remove less material so that edge regions are intentionally left "high"**
  - Minimizes amount of material that needs to be removed in second run
- **Correct edge regions with a smaller spot with subsequent iteration**

Without edge effects compensation:

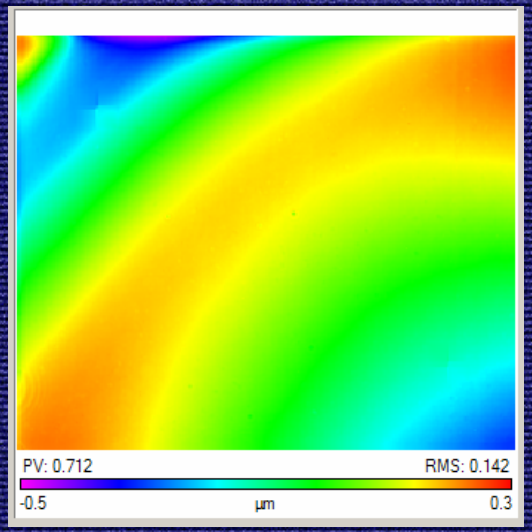
Before polishing | Target figure | After polishing

With edge effects compensation:

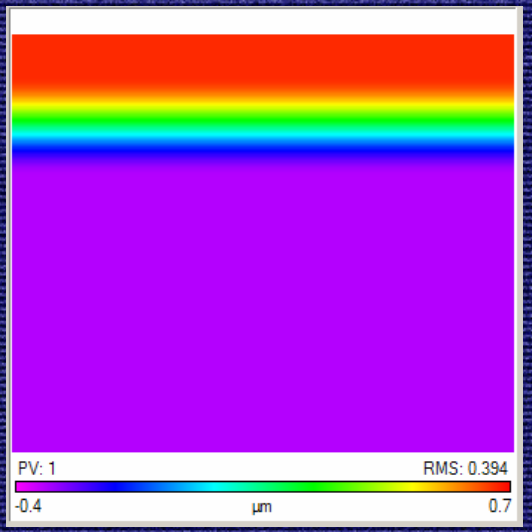


Before polishing | Target figure | After polishing

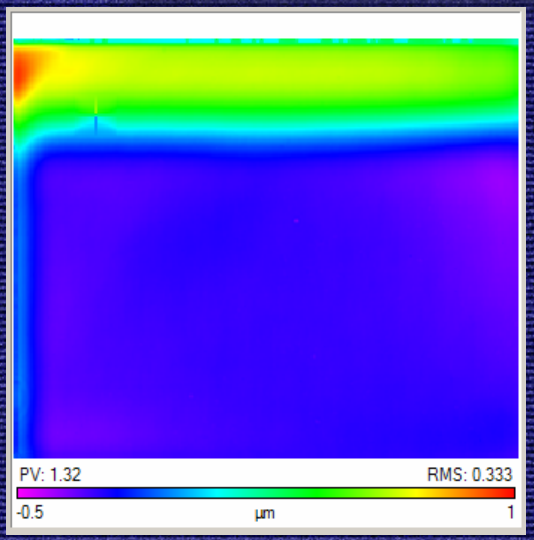
Removal Map Modification



Initial figure map



Target figure map

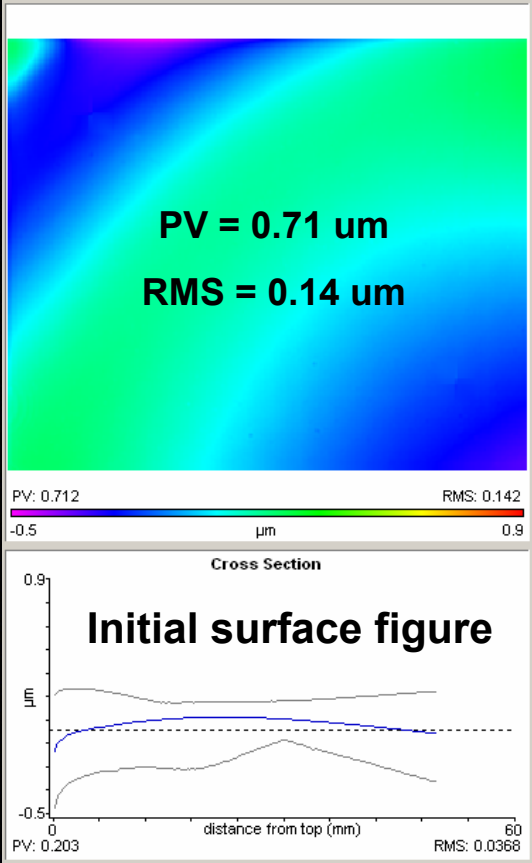


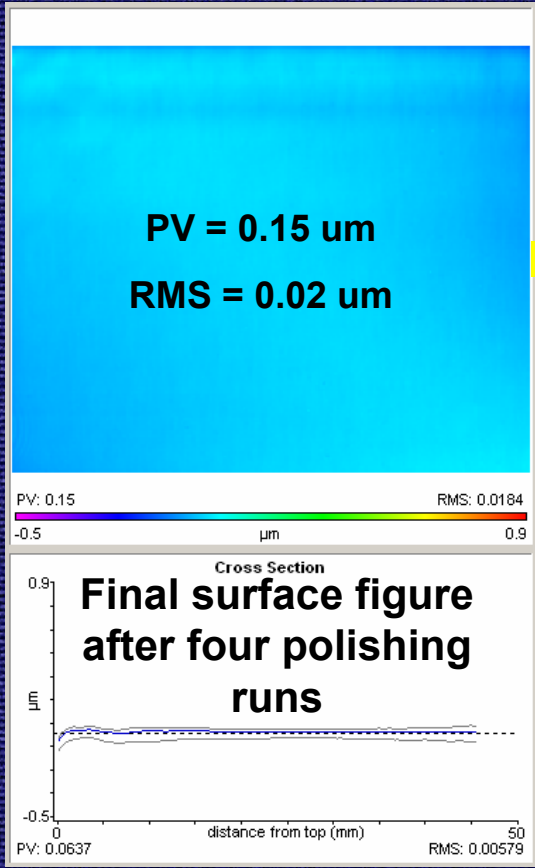
Result figure map

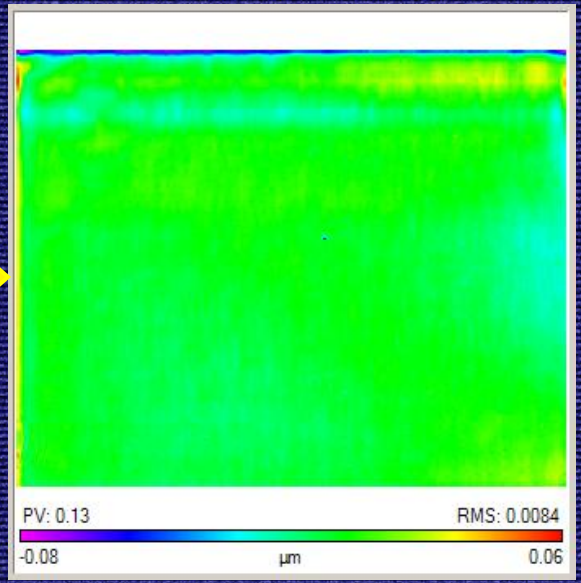
- Choose amplitude, extent, and profile of target figure map edge adjustment to minimize polishing time
- Subsequent polishing runs then performed to correct the "high" edge

Results to Date

- After additional runs, small edge effect remains, but magnitude decreased by > 6x
- Within 2mm of edge







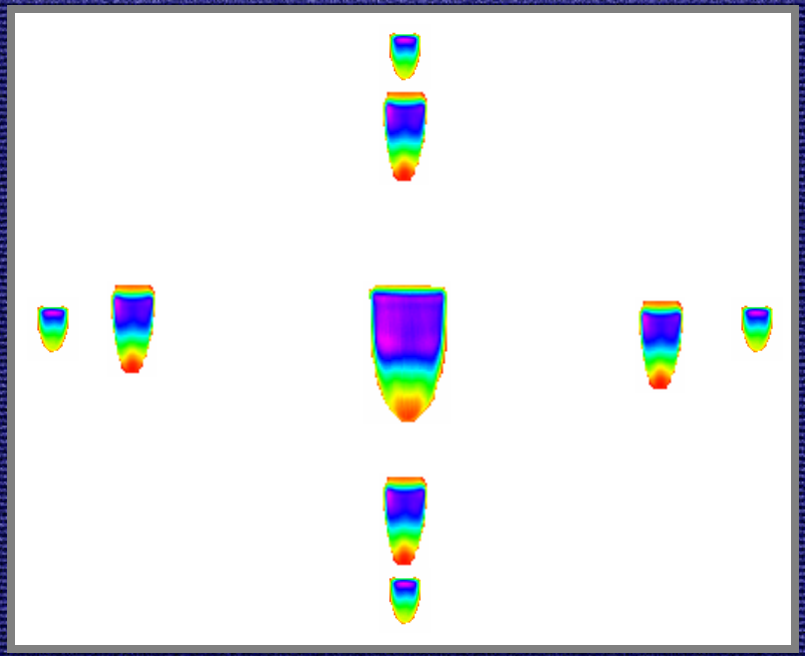
- Final surface on finer scale
- Some edge effect remains
- ~6x improvement compared with "standard" MRF

Summary/Future Strategies

- **Edge effects in MRF are caused by flow interruption at edge**
- **Situation is well understood**
- **Several approaches have been identified to improve performance**
- **"Edge Extension" approach is impractical**
- **Limited success with "Edge Spot Characterization" approach**
- **Significant improvement with "Removal Map Modification"**
  - Additional work would improve efficiency of this approach by choosing more appropriate magnitude, extent and profile of edge
- **Develop variable plunge depth process**
  - Several ways to implement this, but more complex task
  - Should allow polishing closer to the edge with fewer iterations

Variable Plunge Depth

- Extent of edge effect is proportional to spot size
- Use larger spot (higher plunge depth) away from edges to remove material quickly; gradually make spot smaller (lower plunge depth) when approaching edges
- Technically feasible approach



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